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(57) Abstract: In order to improve the repeatability of marine seismic surveys carried out over the same subsurface area using a towed seismic source and a towed array of seismic streamers, the source and streamer array used to perform surveys after the first are depth-controlled and steered laterally so that the source and at least some of the sensors in the streamers occupy at least some of the same positions as the source and sensors of the first survey.

## MARINE SEISMIC SURVEYING

This invention relates to marine seismic surveying, and is more particularly concerned with methods for improving the repeatability of 3D marine seismic surveys of the same subsurface area.

In order to perform a 3D marine seismic survey, an array of marine seismic streamers, each typically several thousand metres long and containing a large number of hydrophones and associated electronic equipment distributed along its length, is towed at about 5 knots behind a seismic survey vessel, which also tows one or more seismic sources, typically air guns. Acoustic signals, or "shots", produced by the seismic sources are directed down through the water into the earth beneath, where they are reflected from the various strata. The reflected signals are received by the hydrophones in the streamers, digitised and then transmitted to the seismic survey vessel, where they are recorded and at least partially processed with the ultimate aim of building up a representation of the earth strata in the area being surveyed.

Often two or more sets of seismic data signals are obtained from the same subsurface area. These sets of seismic data signals may be obtained, for instance, by conducting two or more seismic surveys over the same subsurface area at different times, typically with time lapses between the seismic surveys varying between a few months and a few years. In some cases, the seismic data signals will be acquired to monitor changes in subsurface reservoirs caused by the production of hydrocarbons. The acquisition and processing of time-lapsed three dimensional seismic data signals over a particular subsurface area (commonly referred to in the industry as "4D" seismic data) has emerged in recent years as an important new seismic prospecting methodology.

The purpose of a 4D seismic survey is to monitor changes in the seismic data signals that can be related to detectable changes in geologic parameters. These (not necessarily independent) geologic parameters include fluid fill, propagation velocities, porosity, density, pressure, temperature, settlement of the overburden, etc. Of primary interest are changes taking place in the hydrocarbon reservoir zones of the imaged subsurface volume. Analysing these changes together with petroleum production data assists the interpreter in understanding the complex fluid mechanics of the system of migration paths, traps, draining or sealing faults making up the hydrocarbon reservoir. This provides information regarding how to proceed with the exploitation of the field: where to place new production wells to reach bypassed pay zones and where to place injectors for enhanced oil recovery. This helps to produce a maximum quantity of hydrocarbons from the reservoir at a minimum of cost.

An important precondition to being able to map detectable changes of geological parameters is that the sets of seismic data signals which have been acquired at different times must be calibrated so they match each other. The phrase "match each other" in this context means that images of the seismic data signals reflected from places where no geological parameter changes have taken place must appear substantially identical in the different seismic data signal sets. In reality, this ideal situation is difficult to meet due to the limited repeatability of multiple 3D marine seismic surveys. A data processing technique for alleviating this problem is disclosed in our PCT Patent Application No PCT/IB99/01144 (WO 99/67660). However, there remains a need to improve the repeatability of multiple marine seismic surveys, especially 3D surveys, and it is an object of the present invention to meet this need.

According to the present invention, there is provided a method of repeating a marine seismic survey of a sub-surface area that has been previously surveyed using a first acoustic source and at least one first seismic streamer containing a multiplicity of first acoustic sensors, the method comprising:

storing position signals representative of the respective positions of the first source and at least some of the first sensors for at least some operations of the first source during the previous survey;

towing a second acoustic source and at least one second seismic streamer containing a multiplicity of second acoustic sensors over the subsurface area, the second source being towed along substantially the same path as was followed by the first source during the previous survey; and

steering the second streamer and operating the second source in dependence upon the stored position signals so that for at least some operations of the second source, the second source and at least some of the second sensors occupy substantially the same positions as were occupied by the first source and at least some of the first sensors during the previous survey.

In a preferred implementation of the method, the streamers are steered using laterally-steerable control devices ("birds") of the kind claimed in our United Kingdom Patent No 2 331 971.

Conveniently, the second source is similar to the first source in type (air gun type or marine vibrator type) and geometry (eg number and spatial arrangement of air guns or marine vibrators).

When the previous survey involved an array of first streamers, the method preferably includes using an array of second streamers similar to the array of first streamers, and steering all of the second streamers to achieve substantially the same positions for at least some of the second sensors in each second streamer.

The invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is a somewhat diagrammatic plan view of a seismic survey vessel towing a seismic streamer array in order to perform a marine seismic survey;

Figure 2 is a schematic partly cut away view of a portion of one of the streamers of the streamer array of Figure 1;

Figure 3 is a flow diagram illustrating steps involved in implementing a method in accordance with the present invention of performing a repeat marine seismic survey; and

Figures 4A, 4B and 4C are diagrams useful in illustrating the steps of Figure 3.

The seismic survey vessel shown in Figure 1 is indicated generally at 10, and is preferably as described in our PCT Patent Application No. PCT/GB98/01832 (WO 99/00295). The vessel 10 is provided with a GPS receiver 12 coupled to an integrated computer-based seismic navigation and data processing system 14, and is shown towing a seismic source 15, typically a TRISOR multiple air gun source of the kind described in our US Patent No 4,757,482, and an array 16 of four substantially identical streamers 18. However, it will be appreciated that, in practice, many more than four streamers can be towed, for example by using the techniques described in our PCT Patent Application No PCT/IB98/01435 (WO 99/15913). The streamers 18 are towed by means of their respective lead-ins 20 (ie the high strength steel- or fibre-reinforced electrical or electro-optical cables which convey electrical power, control and data signals between the vessel 10 and the streamers), and their spread is controlled by two MONOWING deflectors, indicated at 22, connected to the respective forward ends 24 of the two outermost streamers. The deflectors 22, which are described in detail in our US Patent No 5,357,892, act in co-operation with respective spreader lines 26 connected between the forward end 24 of each outer streamer 18 and the forward end 24 of its adjacent streamer to maintain a substantially uniform spacing between the streamers.

Each streamer 18 can be as described in our PCT Patent Application No PCT/GB99/01544 (WO 99/60421), and is made up of a large number of substantially identical streamer sections 18a connected together end to end. Each streamer section 18a comprises a tubular outer plastics skin 28 which contains several elongate stress members 30, eg of Kevlar, and a multiplicity of substantially uniformly spaced apart hydrophones 32 separated by kerosene-saturated plastics foam spacer material 34, as best seen in Figure 2.

The forward end 24 of each streamer 18 comprises at least two stretch sections 36, each at least 50 metres long, which serve as vibration dampers to reduce the effect on the streamer of vibrations produced by the towing system connected to the forward end of the streamer.

Each streamer 18 has a plurality of "birds" 38, preferably of the kind described in our PCT Patent Application No PCT/GB97/03507 (WO 98/28636), distributed at 200 metre intervals therealong, for controlling the streamer's depth and steering it laterally. Additionally, each streamer 18 has emitters (or "pingers") 40, typically of the type available from Sonardyne International Ltd of the UK, uniformly distributed therealong, the pingers being interleaved between the birds 38.

The rearward ends 42 of the streamers 28, ie the ends remote from the vessel 10, are connected via respective stretch sections 44 similar to the stretch sections 36 to respective tailbuoys 46, the two outermost tailbuoys being provided with respective pingers 48 similar to the pingers 40 and respective GPS receivers 50.

The array 16 is provided in the region of its forward end 24 with two further buoys or floats 52. More specifically, the further floats 52 are respectively connected to the two outermost streamers 18 at respective watertight electro-optical "tee" connectors 54 positioned between the two stretch sections 36 at the

forward ends 24 of the outermost streamers, so as to be towed by the streamers. The buoys 52 can be substantially identical to the tailbuoys 46, are provided with respective pingers 56 and GPS receivers 58, and are connected to their respective connectors 54 by respective stretch sections 60. Although the buoys 52 are shown in Figure 1 as offset with respect to their streamers for clarity, in practice they are substantially in line with the streamers.

The seismic source 15 is also provided with a GPS receiver, indicated at 62, and an acoustic receiver such as a hydrophone (not shown), and is steerable.

In use, the seismic source 15 and the seismic streamer array 16 are deployed from the vessel 10 and towed at about 5 knots substantially in the configuration shown in Figure 1. The seismic source 15 is periodically fired, eg every 10 seconds or so, and the resulting reflected seismic data signals are detected by the hydrophones 32 in the streamers 18, then digitised and transmitted to the system 14 in the vessel 10 via the lead-ins 20.

Although the source 15 and the streamers 18 are shown in Figure 1 as extending in perfectly straight lines behind the vessel 10, in practice they are frequently subject to lateral displacement, due for example to wind and wave action and currents. So in order to build up a positionally accurate representation of the earth strata in subsurface area being surveyed, it is essential to determine accurately the respective absolute positions (ie in latitude and longitude) of the source 15 and the hydrophones 32 for each shot produced by the source. This is done for the source 15 using the GPS receiver 62. The respective positions of the hydrophones 32 are determined with respect to one or more of the GPS receivers 50, 58 and 62 by triangulation, using an acoustic ranging and positioning system based on the pingers 40, 48 and 56 operating in conjunction with selected ones of the hydrophones 32, as described in our US Patents Nos 4,992,990 and 5,668,775. Thus a completed seismic survey results not only in a vast amount of seismic data, but also a vast amount of positional data defining

the respective positions of source 15 and the hydrophones 32 for each shot produced by the source. From this positional data, the shape of the path or track followed by each streamer 18 throughout the survey can be determined.

When it is desired to use the vessel 10 to perform a repeat survey of a subsurface area previously surveyed (which previous survey may have been carried out by a different contractor using a vessel towing an array of streamers which were not laterally steerable), sufficient positional data from the previous survey is loaded into the system 14 to define the respective tracks followed by the vessel, source and streamers used in the previous survey. Additionally, the source 15 and the array 16 of streamers 18 are deployed in a configuration (relative position of source and streamers as well as the number, length, spread and spacing of the streamers) similar to that used in the previous survey.

From the previous survey positional data stored in the system 14, the system continuously generates data defining the respective shape adopted by each streamer at each shot point in the previous survey: this step is indicated at 64 in Figure 3, with the shape/track of a single streamer being indicated at 66 in Figure 4A. The system 14 is used to cause the vessel 10 to follow as closely as possible the track followed by the vessel used in the previous survey, and the source 15 is also steered to follow as closely as possible the track followed by the source of the previous survey. Concurrently, the system 14 is used to calculate where pre-selected points (or "nodes") along each streamer should be at a given future firing of the source 15. This process is indicated at 68 and 70 in Figure 3, while calculated nodes 72 are shown for one streamer 18 in Figure 4B. Finally, the system 14 produces inputs based on the difference between the present and desired future positions of the nodes 72 for a steering controller 74, which in turn produces at 76 control signals for the birds 38, to cause them to laterally steer the streamer 18 so that the nodes 72 are as close as possible to their desired positions at the correct time, as shown in Figure 4C.

An analogous process is used to steer the source 15.

It will be appreciated that it will not be possible to reproduce precisely the tracks followed by all the equipment of the previous survey. But as long as a significant proportion of the equipment of the second survey is positioned close to the positions occupied by the equipment of the previous survey for significant parts of the survey, the repeatability will be much improved.

Many modifications can be made to the described implementation of the invention.

For example, the steering produced by the birds 38 can be assisted if desired by applying small steering corrections to the MONOWING deflectors 22.

Additionally, the calculation of the nodes 72 can be performed off-line, before the repeat survey is started.

Further, although the invention has been described in the context of a 3D survey using an array of streamers, it is equally applicable to a 2D survey using a single streamer. Also, the source used for the repeat survey need not be identical to that used in the previous survey, while the streamer array used for the repeat survey could be larger or smaller than that used for the previous survey as long as part of it was similar to part of the array used for the previous survey.

## CLAIMS

1. A method of repeating a marine seismic survey of a sub-surface area that has been previously surveyed using a first acoustic source and at least one first seismic streamer containing a multiplicity of first acoustic sensors, the method comprising:

storing position signals representative of the respective positions of the first source and at least some of the first sensors for at least some operations of the first source during the previous survey;

towing a second acoustic source and at least one second seismic streamer containing a multiplicity of second acoustic sensors over the subsurface area, the second source being towed along substantially the same path as was followed by the first source during the previous survey; and

steering the second streamer and operating the second source in dependence upon the stored position signals so that for at least some operations of the second source, the second source and at least some of the second sensors occupy substantially the same positions as were occupied by the first source and at least some of the first sensors during the previous survey.

2. A method as claimed in claim 1, wherein the second streamer is steered using laterally-steerable control devices ("birds") which are connected in series in the streamer and which have two oppositely disposed independently controllable wings.

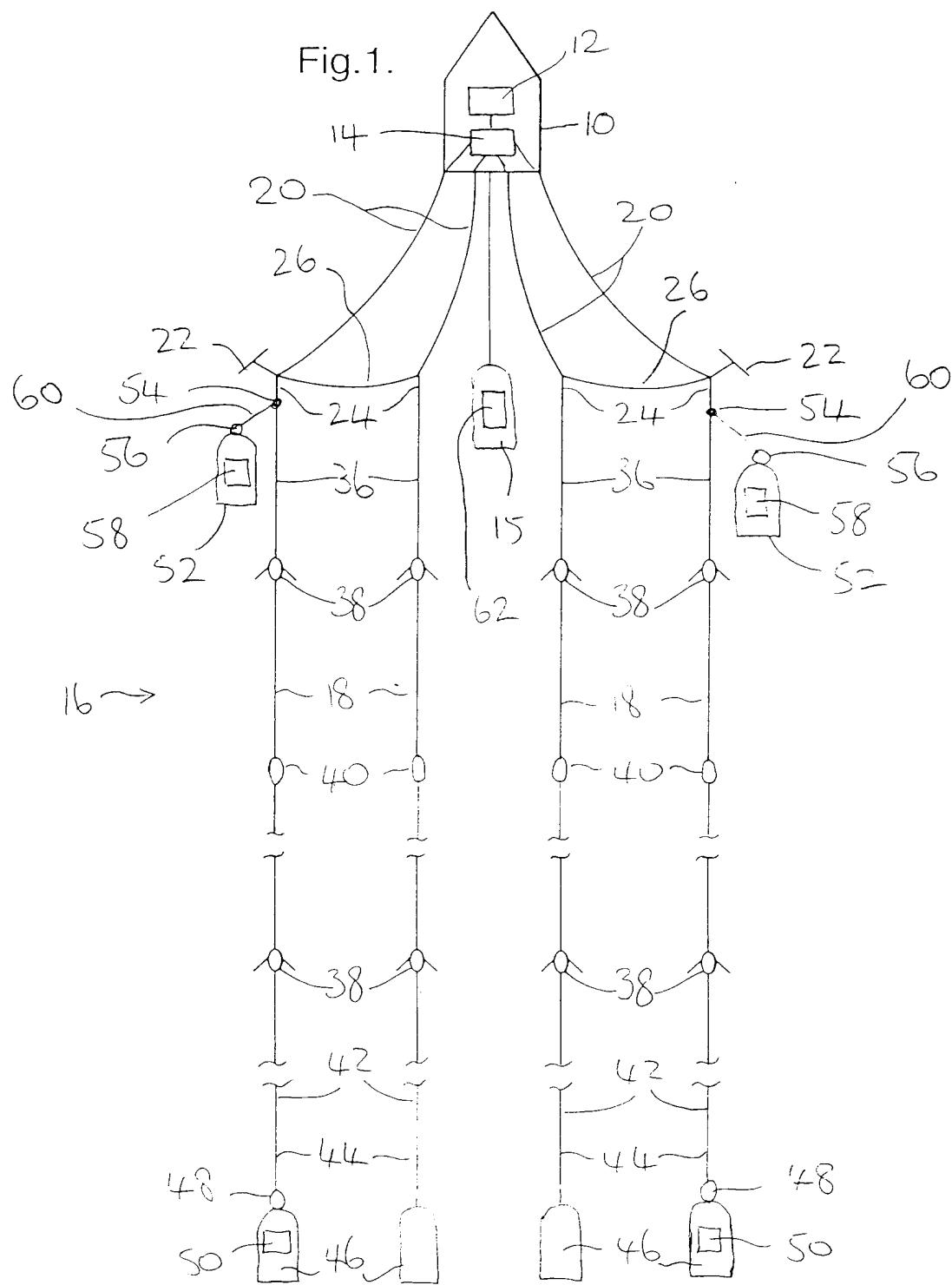
3. A method as claimed in claim 1 or claim 2, wherein the second source is similar to the first source in type (eg air gun type or marine vibrator type) and geometry (eg number and spatial arrangement of air guns or marine vibrators).

4. A method as claimed in any preceding claim, for use where the previous survey involved an array of first streamers, further including using an array of second streamers similar to the array of first streamers, and steering all of the

second streamers to achieve substantially the same positions for at least some of the second sensors in each second streamer.

5. A method as claimed in any preceding claim, wherein the second source is steered to follow substantially the same path as was followed by the first source during the previous survey.

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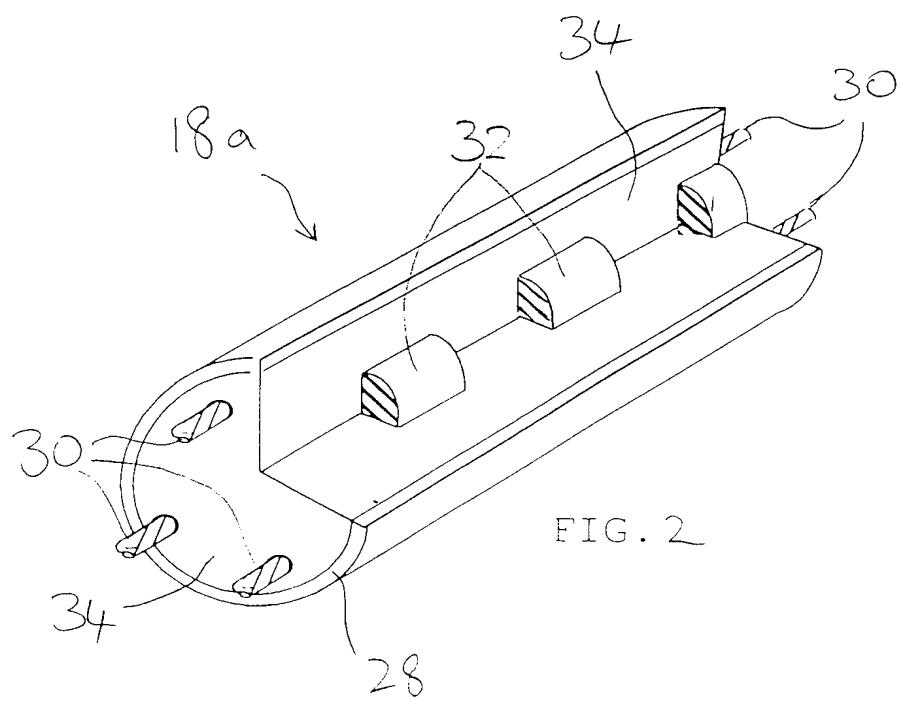


FIG. 2

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# Repeatable Dynamic Marine Seismic Cable Positioning

